

Modern Physics Letters A
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$\Lambda(1405)$ IN CHIRAL SU(3) DYNAMICS

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Received (Day Month Year)

Revised (Day Month Year)

We discuss several aspects of the $\Lambda(1405)$ resonance in relation to the recent theoretical developments in chiral dynamics. We derive an effective single-channel $\bar{K}N$ interaction based on chiral SU(3) coupled-channel approach, emphasizing the important role of the $\pi\Sigma$ channel and the structure of the $\Lambda(1405)$ in $\bar{K}N$ phenomenology. In order to clarify the structure of the resonance, we study the behavior with the number of colors (N_c) of the poles associated with the $\Lambda(1405)$, and argue the physical meaning of the renormalization procedure.

Keywords: $\Lambda(1405)$; chiral dynamics

PACS Nos.: 13.75.Jz, 14.20.-c, 11.30.Rd, 11.15.Pg

1. Introduction

The $\Lambda(1405)$ resonance has been drawing intensive attention. On top of the long-standing problem of its structure (three-quark versus hadronic molecule), new issues have been discussed recently: the influence of the $\Lambda(1405)$ to the $\bar{K}N$ interaction in relation to the possible antikaon bound states in nuclei, and the two-pole structure of the scattering amplitude for the $\Lambda(1405)$. These issues are stimulated by the recent experimental studies as well as theoretical developments of the nonperturbative

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chiral coupled-channel dynamics. Here we address several issues of the $\Lambda(1405)$ in connection with the renewed interests on this resonance.

2. Nonperturbative chiral dynamics

The low energy hadron physics is systematically studied by chiral perturbation theory (ChPT). However, when the hadron interaction is strongly attractive, we certainly need a nonperturbative technique beyond ChPT. This is indeed the case for the $S = -1$ meson-baryon scattering where the leading order interaction in ChPT reads

$$V_{ij} \sim -\frac{C_{ij}}{4f^2}(\omega_i + \omega_j), \quad (1)$$

and the diagonal couplings $C_{\bar{K}N} = 3$ and $C_{\pi\Sigma} = 4$ are attractive enough to generate singularities of scattering amplitude. A nonperturbative chiral approach has been developed in Refs. 1, 2, where the coupled-channel scattering amplitude T_{ij} is determined by solving the Bethe-Salpeter (BS) equation

$$T_{ij} = V_{ij} + V_{il}G_l T_{lj}, \quad (2)$$

with the interaction kernel V_{ij} in Eq. (1). The amplitude constructed in this way reproduces well the K^-p scattering observables, with the $\Lambda(1405)$ resonance being generated from the coupled-channel meson-baryon dynamics. This framework was applied to the various hadron scatterings with the pseudoscalar meson, successfully reproducing experimental data of the scatterings and resonance properties. These remarkable successes in a variety of channels can be understood that the leading order chiral interaction is determined model independently,³ which is the driving force to generate the resonances.⁴

An interesting observation has been made² that the $\Lambda(1405)$ resonance is associated with two poles of the scattering amplitude close each other with the same quantum numbers. A simple explanation of this structure is given in Ref. 5; both the $\bar{K}N$ and $\pi\Sigma$ channels are attractive, and each attractive interaction provides one singularity. Since the sign and the strength of the interaction (1) are determined by the chiral low energy theorem, the two-pole structure of the $\Lambda(1405)$ is a natural consequence of the chiral symmetry in the coupled-channel $\bar{K}N$ - $\pi\Sigma$ system.

3. Effective $\bar{K}N$ interaction based on chiral dynamics

The study of possible bound state of antikaon in nuclei is a hot topic in nuclear physics.⁶ The structure of the $\Lambda(1405)$ is of great importance to these studies, because the only experimental information below $\bar{K}N$ threshold is the spectrum of the $\Lambda(1405)$ in $\pi\Sigma$ channel.

In order to study the few-body nucleus with an antikaon, a realistic $\bar{K}N$ potential is needed, which reproduces the scattering amplitude in vacuum. In order to derive such a potential based on chiral dynamics,⁵ we first construct the single-channel $\bar{K}N$

interaction which incorporates the full coupled-channel effects. Next we approximate this interaction by a local potential in Schrödinger equation, keeping the scattering amplitude the same with the prediction of chiral dynamics.

An important observation in Ref. 5 is that the resonance structure in the $\bar{K}N$ amplitude appears at around 1420 MeV, not in the nominal position of 1405 MeV observed in $\pi\Sigma$ spectrum. The physics behind this observation is the strong $\pi\Sigma$ dynamics which eventually leads to the two-pole structure of the $\Lambda(1405)$. As a consequence of the weaker binding energy, the strength of the effective single-channel $\bar{K}N$ interaction is roughly one half of the phenomenological potential.⁶ The application of this chiral $SU(3)$ potential to the three-body K^-pp system⁷ provides a smaller binding energy than the purely phenomenological approach.

It is also found that the local potential approximation works only at around the threshold and overestimates the amplitude obtained by the BS equation (2), when extrapolated down to $\sqrt{s} < 1400$ MeV. This indicates the substantial uncertainty in the subthreshold extrapolation of the $\bar{K}N$ interaction, which is relevant for the discussion of the deeply bound antikaons in nuclei.

4. Structure of the $\Lambda(1405)$

One of the recent interests in hadron physics is the structure of the hadron resonances. There are several discussions about the structure of the baryon resonances: three-quark versus five-quark, or hadronic molecule versus quark originated structure. In principle, all these structures eventually stem from QCD dynamics and mix each other. Nevertheless it helps our physical understanding to decompose a resonance state, and inspect the dominant component for the resonance. For instance, the $\Lambda(1405)$ can be schematically written as

$$|\Lambda(1405)\rangle = N_3|qqq\rangle + N_5|qqq\bar{q}\bar{q}\rangle + N_{MB}|B\rangle|M\rangle + \dots, \quad (3)$$

where the third term is understood as the dynamical meson-baryon component other than the CDD pole,⁸ which could be identified within the scattering theory of hadrons.⁹ One naively expects that the baryonic resonances in chiral dynamics are dominated by this component, but this is not always true and substantial CDD pole contribution was found for some resonances.¹² Here we attempt to unveil the structure in Eq. (3) by studying the N_c scaling of the $\Lambda(1405)$ poles¹⁰ and by utilizing the renormalization condition.¹¹

The study of the N_c behavior is a powerful tool to clarify the quark content of hadron resonances,¹² since the N_c scalings are known for $\bar{q}q$ mesons and qqq baryons.¹³ In Ref. 10, we study the N_c behavior of the $\Lambda(1405)$ resonance in chiral dynamics. Because of the nontrivial N_c dependence of the leading order chiral interaction found in Ref. 4, the attractive $\bar{K}N$ interaction remains finite in the large N_c limit. As a consequence, the $\bar{K}N$ bound state exists in the large N_c limit. The two poles of the $\Lambda(1405)$ behave differently from the scaling of ordinary qqq baryons, indicating that the N_3 component in Eq. (3) does not dominate the $\Lambda(1405)$.

In the framework of nonperturbative chiral dynamics, we propose a method to distinguish the dynamical component from the CDD pole contribution by studying the physical meaning of the renormalization condition.¹¹ We point out that the previous phenomenological chiral models have included the CDD pole contribution in the loop function. With a natural renormalization condition, we extract the CDD pole contribution hidden in the loop function into the kernel interaction V , as it should be in the framework of the N/D method. By examining the phenomenological chiral models, we find that the amplitude for the $N(1535)$ requires the CDD pole at around 1.7 GeV, while that for the $\Lambda(1405)$ lies at an irrelevant energy of 17 GeV. This implies that the N_{MB} component dominates the $\Lambda(1405)$, while substantial quark-originate contributions N_3, N_5, \dots are expected in the $N(1535)$.

5. Summary

The $\Lambda(1405)$ is very unique baryon resonance, and plays an important role in various fields of nuclear and hadron physics. The strong $\bar{K}N$ interaction is the principle ingredient of the $\Lambda(1405)$, but at the same time we should appreciate the strong $\pi\Sigma$ interaction, from the viewpoint of chiral symmetry. The two-pole structure of the $\Lambda(1405)$ is no longer a theoretical issue of hadron spectroscopy, but is relevant for the discussion of $\bar{K}N$ phenomenology. In order to understand the structure of the $\Lambda(1405)$, we make use of the N_c scaling and renormalization condition. Both the analyses consistently imply that the $\Lambda(1405)$ would be dominated by the dynamical content. The precise experimental data on $\bar{K}N$ scattering length and $\pi\Sigma$ spectrum is highly desired in order to reduce the theoretical uncertainty to explore the strongly interacting $\bar{K}N$ - $\pi\Sigma$ system, and to clarify the structure of the $\Lambda(1405)$ resonance.

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